MOTOROLA
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Application Note

APPLICATIONS OF FERRULED COMPONENTS TO FIBER OPTIC SYSTEMS

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This application note is intended to acquaint the designer of fiber optic (F/O) systems with some of the features and considerations to be made in the use of the Motorola Fiber Optic Active Component (FOAC) family of devices. In particular, the basic fiber optic system losses are discussed, an understanding of which is necessary for proper interpretation and use of the typical data sheet information. It assumes some familiarity on the part of the reader with F/O technology. A list of references covering the basics is given in the bibliography.

THE MOTOROLA FERRULED LED

Construction and Optical Characteristics

This device is constructed by assembling an infrared light emitting diode (LED) in a package suitably configured to mate with and become an integral part of a fiber optic connector. This active connector concept is illustrated in Figure 1(a). The ferruled semiconductor and its exploded view are illustrated in Figures 1(b) and 1(c).

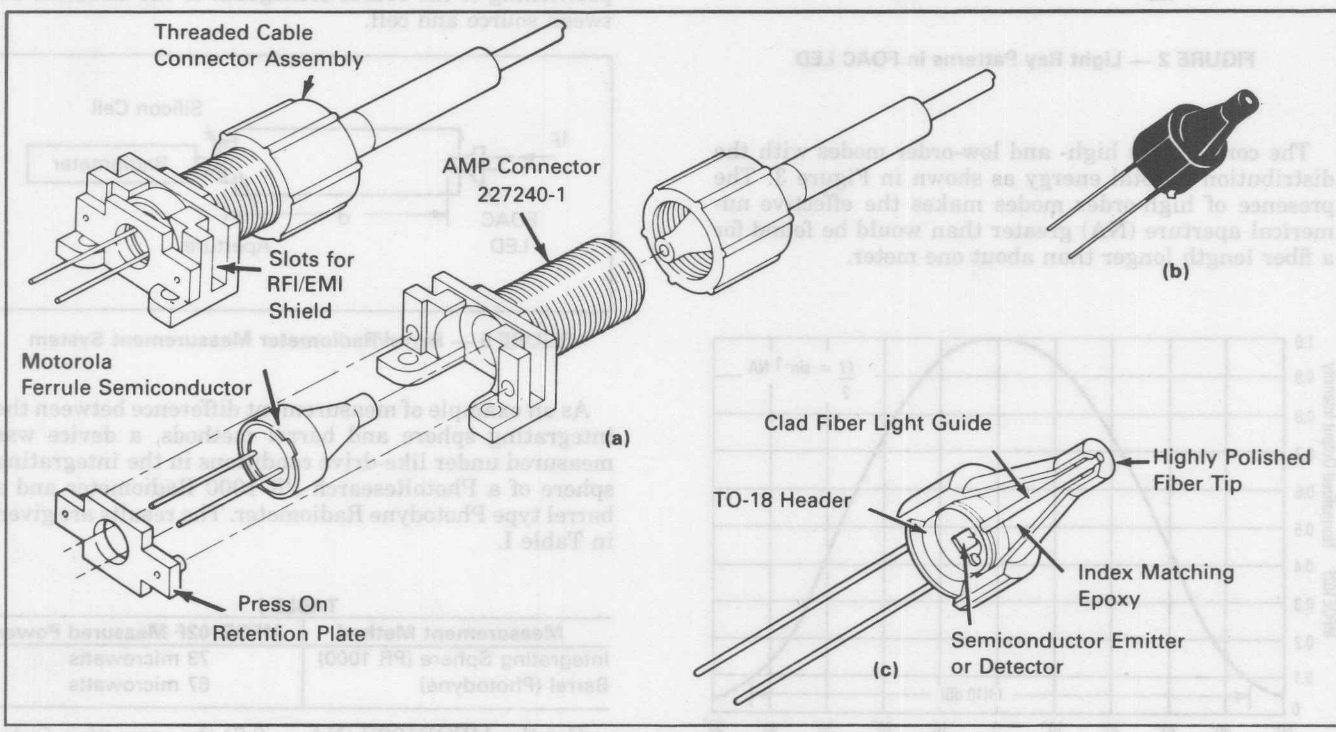

FIGURE 1 — Motorola Fiber Optic Active Component (FOAC)
(a) Package/Connector Concept
(b) External View of FOAC
(c) Exploded View of FOAC

A depiction of the light emission pattern of the LED is shown in Figure 2. The fiber cladding carries less than five percent of the total output power since most clad modes are absorbed by the high index of refraction epoxy.

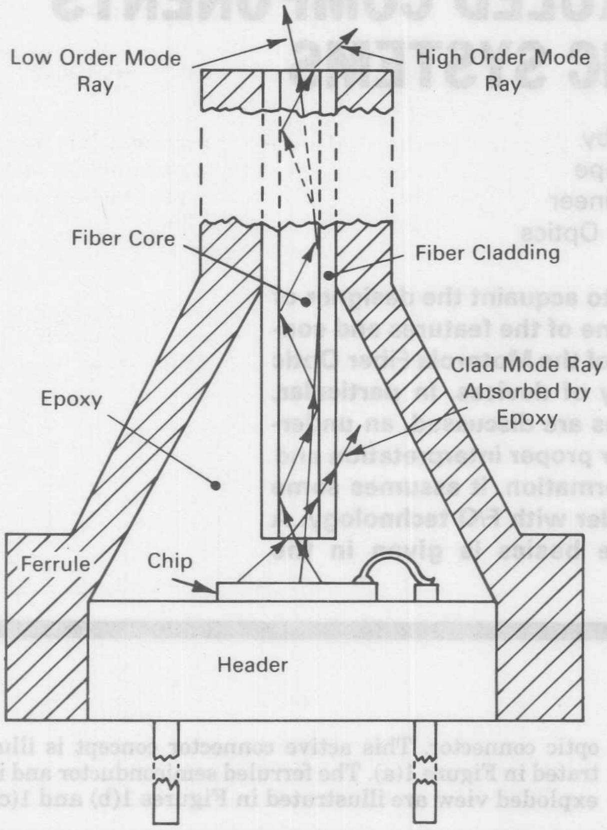

FIGURE 2 — Light Ray Patterns in FOAC LED

The core carries high- and low-order modes with the distribution of total energy as shown in Figure 3. The presence of high-order modes makes the effective numerical aperture (NA) greater than would be found for a fiber length longer than about one meter.

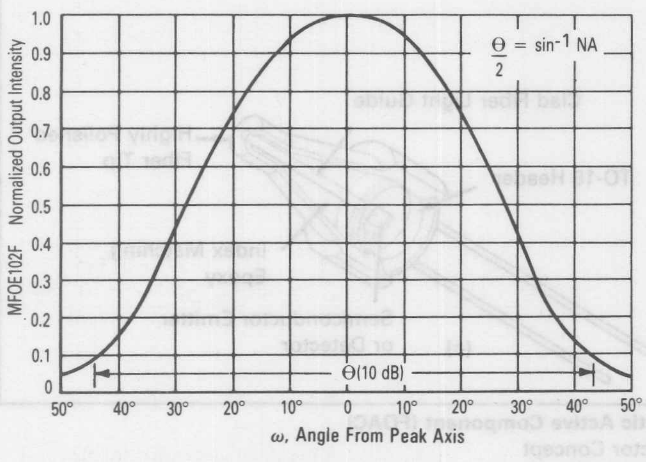

FIGURE 3 — Light Emission Pattern for FOAC LED

Measurement of Output Power

There are several methods currently in use for measuring the output of F/O sources.

The integrating sphere method shown in Figure 4 collects the power radiated from the source in all directions and directs it to the silicon detector cell of a radiometer. It is the most repeatable technique of measurement since it is effectively independent of geometry. However, since it is not sensitive to the NA of the source, it does not enable the user to predict the amount of the measured power that can be coupled from the source into a fiber.

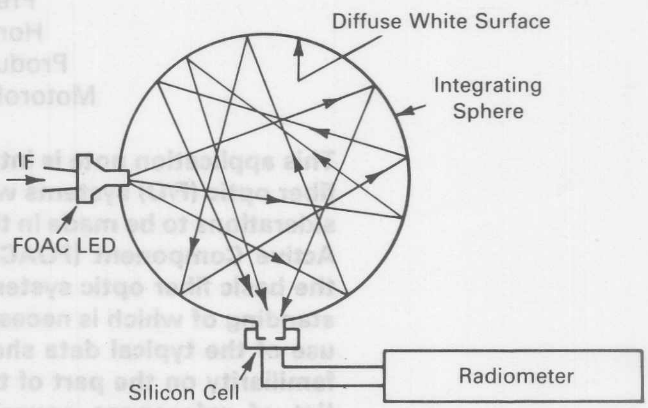

FIGURE 4 — Integrating Sphere/Radiometer Measurement Method

The barrel method, Figure 5, simulates the condition of coupling into a fiber. Only the power that passes through the aperture is measured. Repeatability requires exact duplication of the aperture size, the distance between the source and the silicon cell, and the accurate positioning of the source orthogonal to the direction between source and cell.

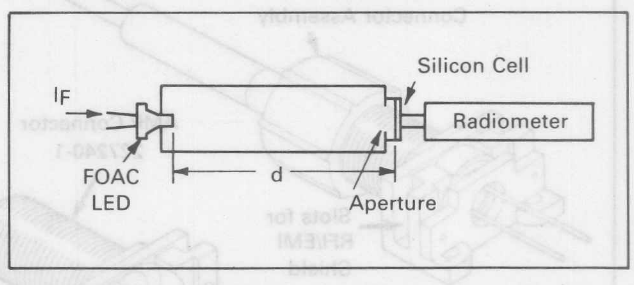

FIGURE 5 — Barrel/Radiometer Measurement System

As an example of measurement difference between the integrating sphere and barrel methods, a device was measured under like-drive conditions in the integrating sphere of a PhotoResearch PR 1000 Radiometer and a barrel type Photodyne Radiometer. The results are given in Table I.

TABLE I

Measurement Method	MFOE102F Measured Power
Integrating Sphere (PR 1000)	73 microwatts
Barrel (Photodyne)	67 microwatts

For the MFOE102F (NA = 0.7) the correction factor between the barrel and the integrating sphere is 0.91. Devices with smaller NAs will have a correction factor approaching 1.0.

THE MOTOROLA FERRULED DETECTOR

Construction and Optical Characteristics

The detector members of the FOAC family utilize the same construction as the LED. Again, because of the short length of the fiber in the ferrule, the effective NA is larger than found for longer sections of the same type of fiber. The angular response for the detector is similar to the emission pattern for the LED, Figure 6.

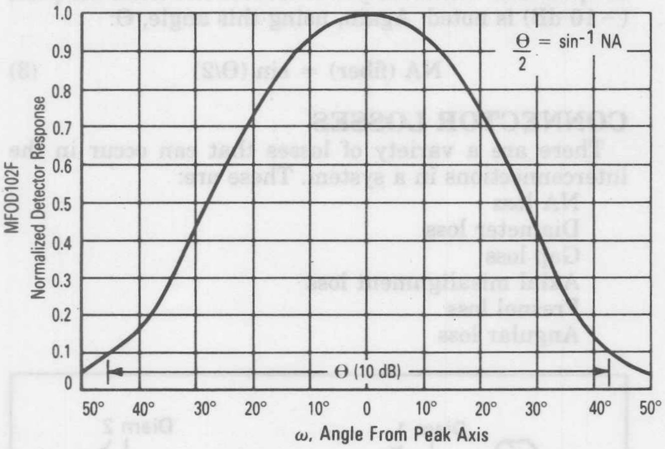

FIGURE 6 — Light Response Pattern for FOAC Detector

Measurement of Responsivity

The response of the detectors is given in output voltage or current per unit of optical power coupled into the detector's input port. It does not include losses (see Fresnel and connector losses later in this bulletin) between the power source and the input port since these are a function of each individual system's variables.

The FOAC detector responsivity is measured by connecting a FOAC LED to a one meter length of fiber that is connected to a simulated detector ferrule, see Figure 7. The power launched from the simulated ferrule is measured in an integrating sphere, and is a true measure of the actual power coupled into a ferrule detector. The power measured by the sphere/radiometer is recorded.

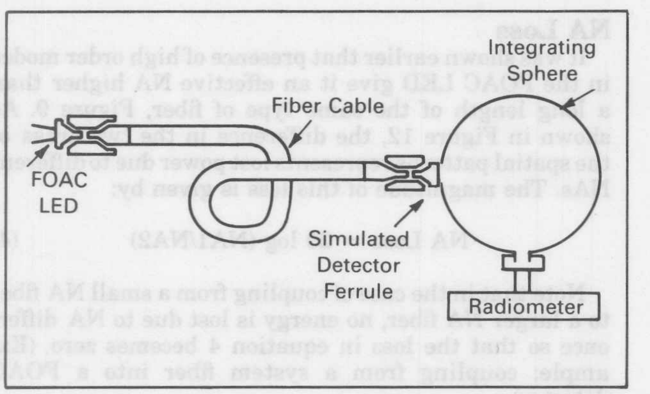

FIGURE 7 — Calibration of Light Source for Detector Responsivity Measurement

The detector to be measured is then connected to the fiber in place of the simulated ferrule, Figure 8, and the output voltage or current is noted. The responsivity for the detector is taken as the ratio of the output voltage or current to the power as measured by the integrating sphere.

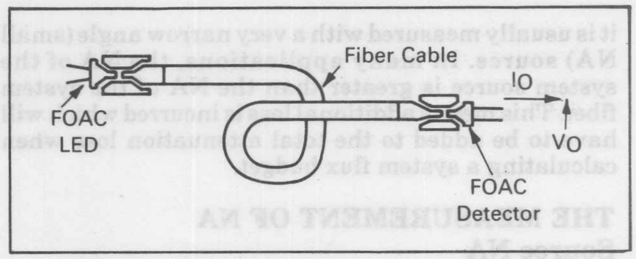

FIGURE 8 — Detector Responsivity Measurement

OPTICAL FIBERS

To calculate the total losses for a system, it is important to know and understand the parameters of the system fiber. The two most critical parameters are:

1. Output NA of the fiber
2. Fiber attenuation

Output NA of a Fiber

The output NA of a fiber is a function of its length, as shown in Figure 9. Most fiber manufacturers specify NA. If it is not available for a particular fiber, it can be measured as shown later in this bulletin.

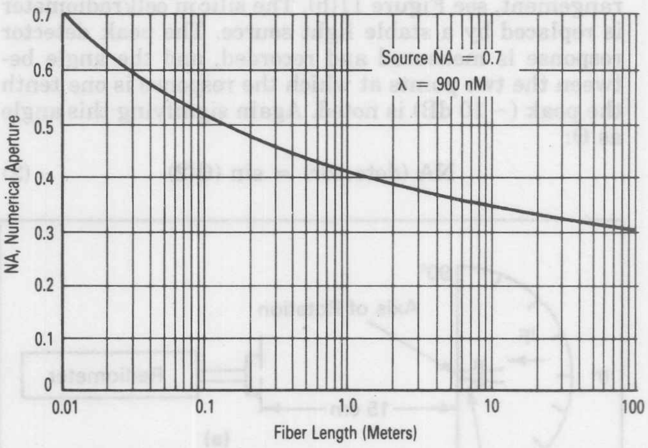

FIGURE 9 — NA versus Length for a Sample Fiber

Fiber Attenuation

The attenuation characteristic of a fiber is usually specified in dB per meter or dB per kilometer. If it is given as a single value, the manufacturer will specify the wavelength of measurement. Usually the attenuation is given graphically as a function of wavelength. Figure 10 shows several examples. The specified attenuation does not contain losses due to NA changes, since

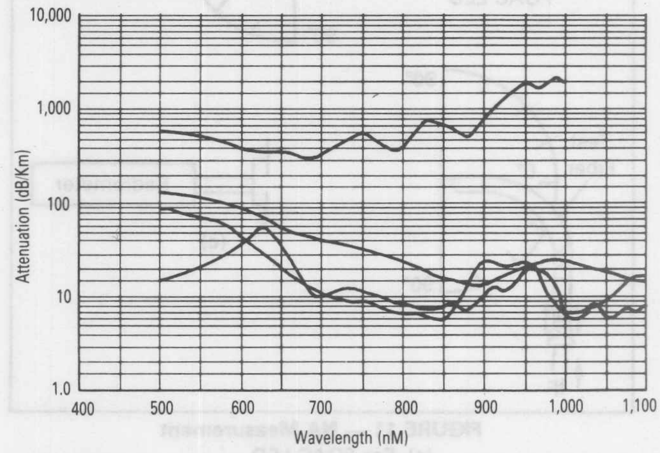

FIGURE 10 — Attenuation versus Wavelength for Several Fibers

it is usually measured with a very narrow angle (small NA) source. In many applications, the NA of the system source is greater than the NA of the system fiber. This means additional loss is incurred which will have to be added to the total attenuation loss when calculating a system flux budget.

THE MEASUREMENT OF NA

Source NA

The measurement of NA for an LED source can be made as shown in Figure 11(a). The power from the source is measured by a silicon cell/radiometer through a very small aperture. The peak power level is measured and recorded. The source is rotated and the angle between the two points at which the power level drops to one tenth the peak power level (−10 dB) is noted. Signifying this angle as Θ, the source NA is calculated:

$$\text{NA (source)} = \sin(\Theta/2) \quad (1)$$

Detector NA

The NA for a detector is measured in a similar arrangement, see Figure 11(b). The silicon cell/radiometer is replaced by a stable light source. The peak detector response is measured and recorded, and the angle between the two points at which the response is one tenth the peak (−10 dB) is noted. Again signifying this angle as Θ:

$$\text{NA (detector)} = \sin(\Theta/2) \quad (2)$$

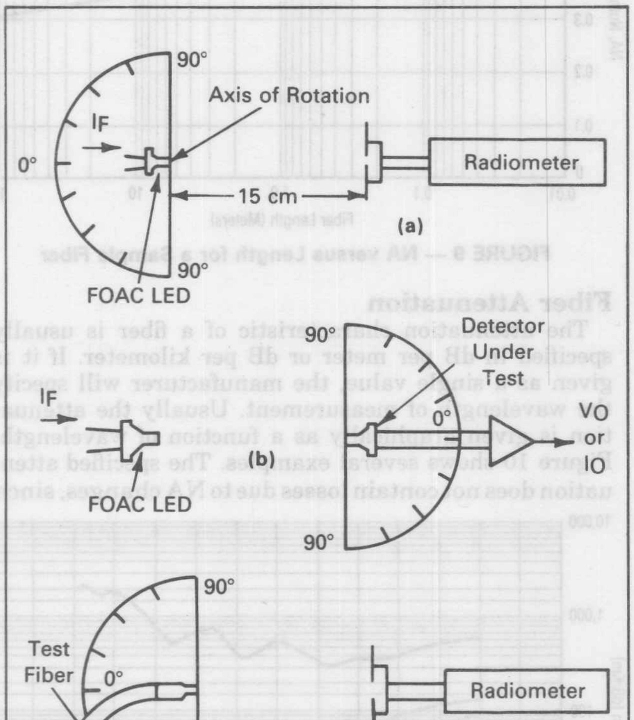

FIGURE 11 — NA Measurement
(a) For FOAC LED
(b) For FOAC Detector
(c) For Fiber

Fiber NA

If the NA of a fiber is not known, it can be measured. The fiber to be tested is terminated in standard cable connectors (AMP Part #530954). One end of the fiber to be measured is connected to a FOAC LED. The other end of the fiber is directed at a silicon cell/radiometer, Figure 11(c). The peak power level from the fiber is recorded. The end of the fiber is then rotated and the angle between the points at which the power level is one tenth the peak (−10 dB) is noted. Again, using this angle, Θ:

$$\text{NA (fiber)} = \sin(\Theta/2) \quad (3)$$

CONNECTOR LOSSES

There are a variety of losses that can occur in the interconnections in a system. These are:

- NA loss
- Diameter loss
- Gap loss
- Axial misalignment loss
- Fresnel loss
- Angular loss

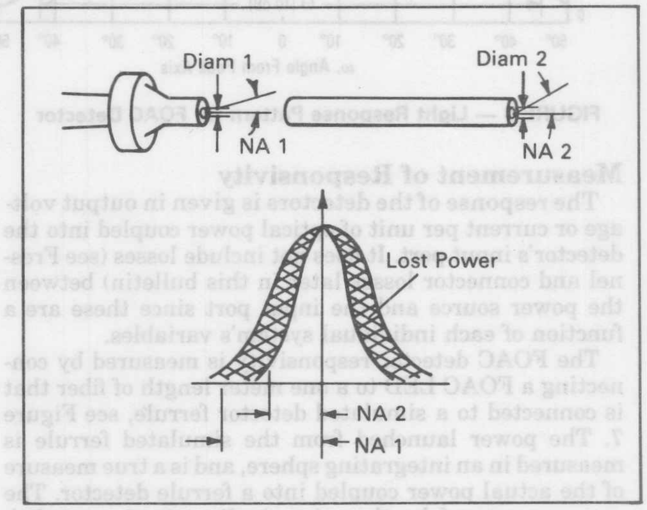

FIGURE 12 — NA Loss

NA Loss

It was shown earlier that presence of high order modes in the FOAC LED give it an effective NA higher than a long length of the same type of fiber, Figure 9. As shown in Figure 12, the difference in the two areas of the spatial patterns represents lost power due to different NAs. The magnitude of this loss is given by:

$$\text{NA Loss} = 20 \log (\text{NA1}/\text{NA2}) \quad (4)$$

Note that in the case of coupling from a small NA fiber to a larger NA fiber, no energy is lost due to NA difference so that the loss in equation 4 becomes zero. (Example: coupling from a system fiber into a FOAC detector)

Diameter Loss

If two fibers of different diameters are coupled, an additional loss may be incurred. It is given by:

$$\text{Diameter Loss} = 20 \log (\text{Dia1}/\text{Dia2}) \quad (5)$$

Again, if the receiving fiber has a diameter greater than the source fiber, Figure 12, the diameter loss reduces to zero.

Gap Loss

Ideally, two fibers would be joined such that no gap exists between them. In practice a small gap is intentionally introduced to prevent mechanical damage to the fiber surfaces. The Motorola FOAC devices and AMP connector bushings are designed to hold this gap to about 0.1 mm. The result of variations in the gap for several sample NAs is given in Figure 13.

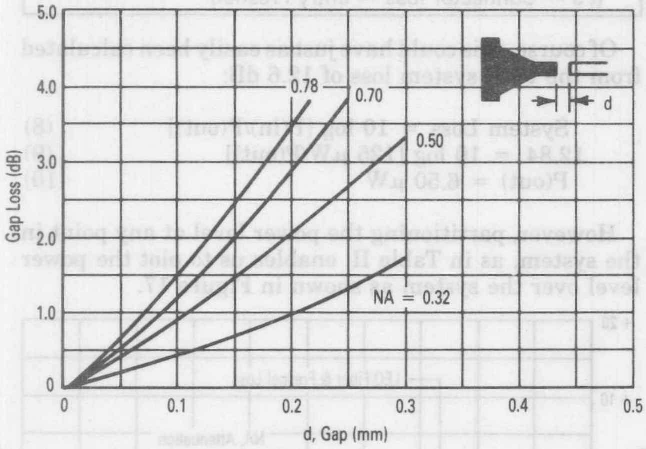

FIGURE 13 — Gap Loss

Axial Misalignment Loss

If two connected fibers are not concentric there will be an obvious loss of power. The effect of this misalignment for several NAs is shown in Figures 14(a), 14(b), and 14(c). The effect of gap separation is also included in these graphs.

FIGURE 14(a)

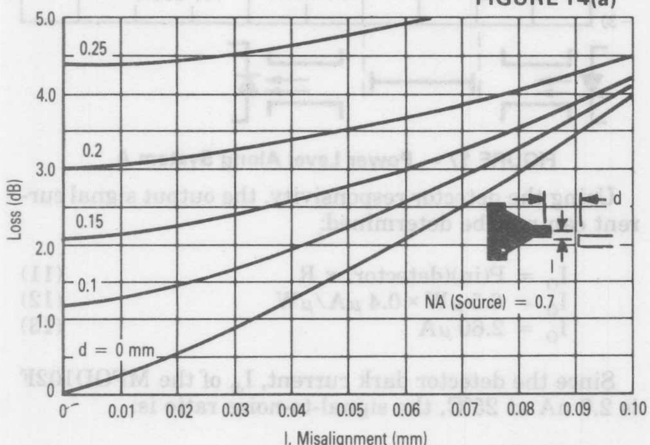

FIGURE 14(b)

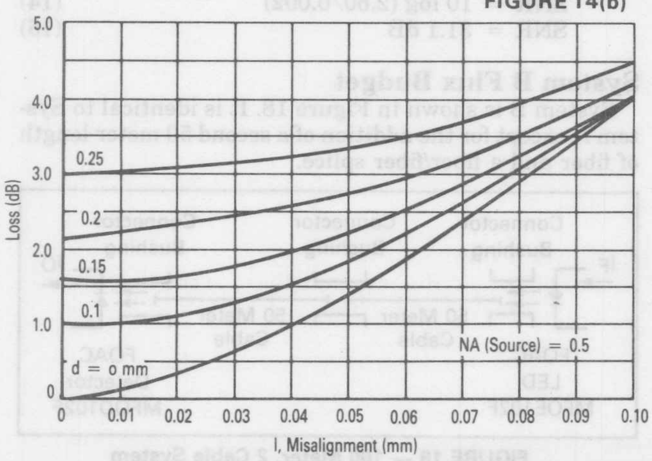

FIGURE 14(c)

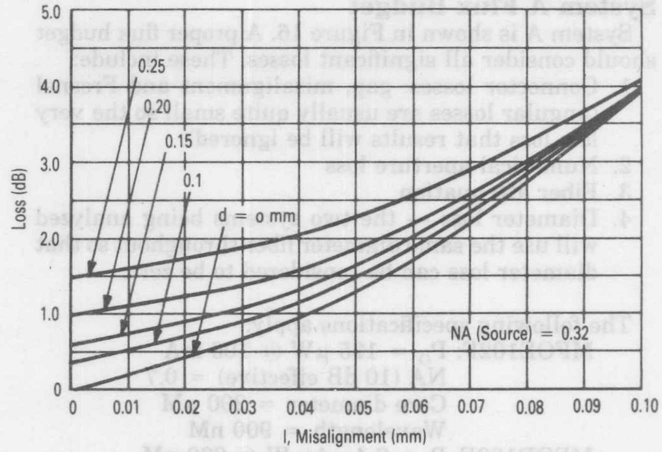

FIGURE 14 — Misalignment Loss

Fresnel Loss

As light passes through any interface, some energy is transmitted and some reflected. The amount of energy lost is a function of the indices of refraction of the materials forming the interface. For the FOAC family of devices and glass core fibers this loss is a fairly consistent 0.2 dB per interface.

Angular Loss

If the surfaces of the two connected fiber ends are not parallel, an additional loss is incurred. The magnitude of this is shown in Figure 15.

FLUX BUDGET

Once the various losses in a system have been identified and quantified, it is a relatively simple exercise to calculate the total system loss and thus predict system performance. To illustrate this, and to highlight a major loss element in systems, two examples will be considered. In each case an MFOE102F LED is used for the source and an MFOD102F PIN diode as the detector. System A uses a 50 meter length of cable, while system B uses two 50 meter lengths joined by a fiber/fiber splice.

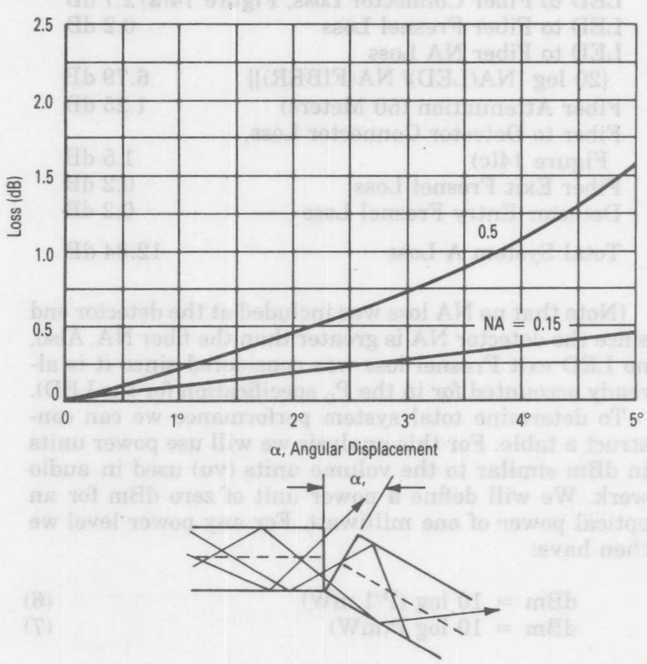

FIGURE 15 — Angular Loss

System A Flux Budget

System A is shown in Figure 16. A proper flux budget should consider all significant losses. These include:

1. Connector losses: gap, misalignment and Fresnel (angular losses are usually quite small so the very low loss that results will be ignored).
2. Numerical aperture loss
3. Fiber attenuation
4. Diameter loss — the two systems being analyzed will use the same diameter fiber throughout so that diameter loss can be considered to be zero.

The following specifications apply:

MFOE102F: P_O = 125 μW @ 100 mA
NA (10 dB effective) = 0.7
Core diameter = 200 μM
Wavelength = 900 nM

MFOD102F: R = 0.4 μA/μW @ 900 nM
NA (10 dB effective) = 0.7
Core diameter = 200 μM
I(dark) = 2.0 nA @ 25°C

Fiber: Length = 50 M
Attenuation = 25 dB/Km @ 900 nM, Figure 10
NA @ 50 M = 0.32
Core diameter = 200 μM

Connectors: Gap = 0.15 mm typical
Misalignment = 0.05 mm typical

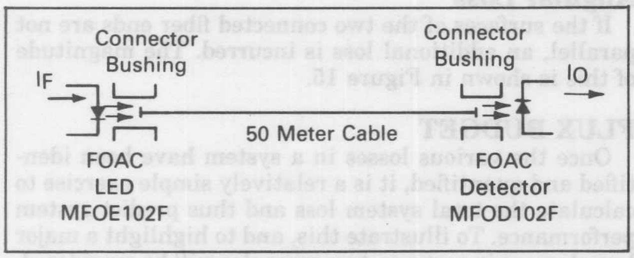

FIGURE 16 — 50 Meter F/O System

The total system loss can now be calculated:

LED to Fiber Connector Loss, Figure 14(a)	2.7 dB
LED to Fiber Fresnel Loss	0.2 dB
LED to Fiber NA Loss {20 log [NA(LED)/ NA(FIBER)]}	6.79 dB
Fiber Attenuation (50 Meters)	1.25 dB
Fiber to Detector Connector Loss, Figure 14(c)	1.5 dB
Fiber Exit Fresnel Loss	0.2 dB
Detector Entry Fresnel Loss	0.2 dB
Total System A Loss	12.84 dB

(Note that no NA loss was included at the detector end since the detector NA is greater than the fiber NA. Also, no LED exit Fresnel loss was considered since it is already accounted for in the P_O specification for the LED).

To determine total system performance we can construct a table. For this analysis we will use power units in dBm similar to the volume units (vu) used in audio work. We will define a power unit of zero dBm for an optical power of one milliwatt. For any power level we then have:

$$\text{dBm} = 10 \log (P/1\ \text{mW}) \quad (6)$$
$$\text{dBm} = 10 \log P(\text{mW}) \quad (7)$$

The table for system analysis now becomes:

TABLE II

Point in the System	Power Units (dBm)	P (μW)
P1: LED @ 100 mA	− 9.03	125
P2: Power in Fiber (P1 — Connector loss — Fresnel loss)	− 11.93	
P3: Power from Fiber (P2 — NA loss — Attenuation — exit Fresnel)	-20.17	
P4: Power into Detector (P3 — Connector loss — entry Fresnel)	-21.87	6.5

Of course, this could have just as easily been calculated from the total system loss of 12.6 dB:

$$\text{System Loss} = 10 \log [P(\text{in})/P(\text{out})] \quad (8)$$
$$12.84 = 10 \log [125\ \mu\text{W}/P(\text{out})] \quad (9)$$
$$P(\text{out}) = 6.50\ \mu\text{W} \quad (10)$$

However, partitioning the power level at any point in the system, as in Table II, enables us to plot the power level over the system as shown in Figure 17.

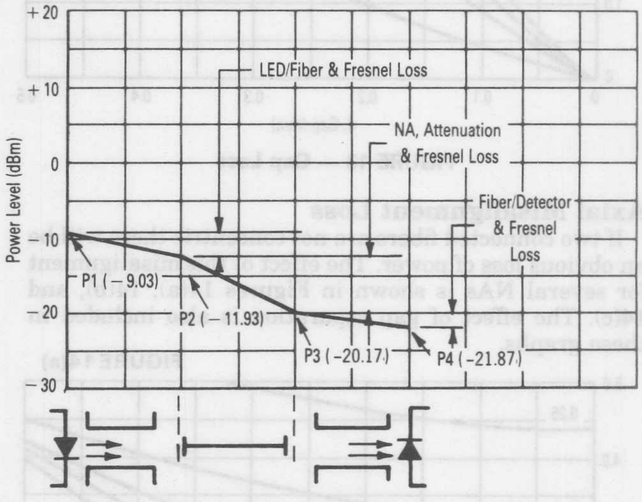

FIGURE 17 — Power Level Along System A

Using the detector responsivity, the output signal current can now be determined:

$$I_O = P(\text{in})(\text{detector}) \times R \quad (11)$$
$$I_O = 6.5\ \mu\text{W} \times 0.4\ \mu\text{A}/\mu\text{W} \quad (12)$$
$$I_O = 2.60\ \mu\text{A} \quad (13)$$

Since the detector dark current, I_d, of the MFOD102F is 2.0 nA at 25°C, the signal-to-noise ratio is:

$$\text{SNR} = 10 \log (2.60/0.002) \quad (14)$$
$$\text{SNR} = 31.1\ \text{dB} \quad (15)$$

System B Flux Budget

System B is shown in Figure 18. It is identical to System A except for the addition of a second 50 meter length of fiber and a fiber/fiber splice.

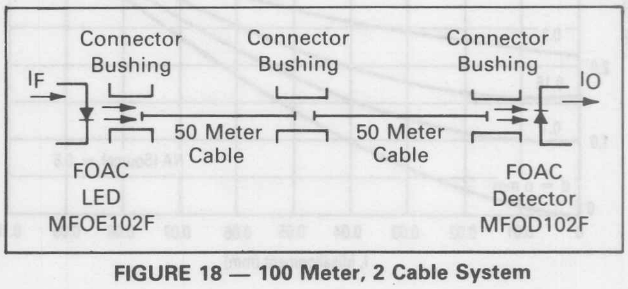

FIGURE 18 — 100 Meter, 2 Cable System

In calculating system losses it is important to note that the NA of 100 meters of fiber is 0.31, per Figure 9. It is independent of the presence of the splice at the midpoint, since the second 50 meters continues to strip high order modes. Another way of looking at it is to consider a replot of Figure 9. This is shown in Figure 19. The difference is that the NA at zero is the NA of the source, in this case the 0.32 exit NA of the first 50 meter length. At long distances the cable will still approach the same asymptotic value as in Figure 9. In Figure 19 it can be seen that the curve passes through 0.31 at 50 meters. So a 50 meter cable with a beginning NA of 0.32, and a 100 meter cable starting with an NA of 0.7 will both have an exit NA of 0.31. (This is true of course only for this particular cable)

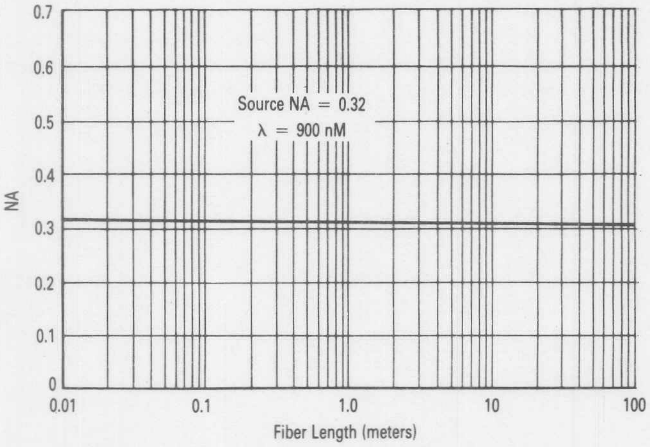

FIGURE 19 — NA versus Length for a Sample Fiber

Calculating system loss:

LED to Fiber Connector Loss, Figure 14(a)	2.7 dB
Fiber 1 Entry Fresnel Loss	0.2 dB
LED to Fiber 1 NA Loss	6.79 dB
Fiber 1 Attenuation	1.25 dB
Fiber 1 Exit Fresnel Loss	0.2 dB
Fiber/Fiber Connector Loss	1.50 dB
Fiber 2 Entry Fresnel Loss	0.2 dB
Fiber 1/Fiber 2 NA Loss	0.28 dB
Fiber 2 Attenuation	1.25 dB
Fiber 2 Exit Fresnel Loss	0.2 dB
Fiber to Detector Connector Loss	1.5 dB
Detector Entry Fresnel Loss	0.2 dB
Total System B Loss	16.27 dB

The power level system analysis is:

TABLE III

Point in the System	Power Units (dBm)	P (μW)
P1: LED @ 100 mA	−9.03	125
P2: Power in Fiber 1 (P1 — Connector Loss — Fresnel Loss)	−11.93	
P3: Power from Fiber 1 (P2 — NA loss — Attenuation — Fresnel Loss)	-20.17	
P4: Power in Fiber 2 (P3 — Connector Loss — Fresnel Loss)	-21.87	
P5: Power from Fiber 2 (P4 — NA Loss — Attenuation — Fresnel Loss)	-23.60	
P6: Power into Detector (P5 — Connector Loss — Fresnel Loss)	-25.30	2.95

The power level along System B is plotted in Figure 20.

The output signal is now calculated:

$$I_O = 2.95\ \mu W \times 0.4\ \mu A/\mu W \quad (16)$$
$$I_O = 1.18\ \mu A \quad (17)$$

The SNR for System B is:

$$SNR = 10 \log (1.18/0.002) \quad (18)$$
$$SNR = 28\ dB \quad (19)$$

It is now of interest to compare the losses in System A with those in System B. At first thought, it might seem that doubling the system length should approximately double the system loss. If the dominant loss mechanism were fiber attenuation, this might be true.

However, as Figures 17 and 20 show, the greatest loss occurs in the first 50 meters of fiber. Since the Fiber attenuation and Fresnel loss for any 50 meter length of this cable is essentially constant at fixed wavelength, the major loss has to be a result of the NA loss from the FOAC LED to the fiber. As shown in the analysis of the two systems this loss is 6.79 dB. As a percentage of the total loss in the two systems, it represents 53% in System A and 42% in System B.

Therefore, in designing a system, the greatest loss will usually be incurred at the front end of the system where the LED couples to the system fiber. One way to combat this is to select fibers with large NAs. However, this will reduce the high frequency capability of the system by increasing pulse dispersion distortion, so the designer is faced with making a tradeoff between system length, or SNR and high-frequency performance.

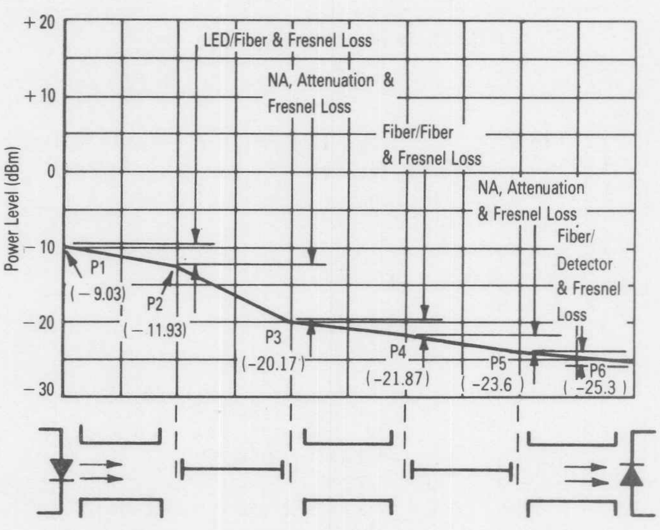

FIGURE 20 — Power Level Along System B

SUMMARY

The packaging concept used in the Motorola FOAC line of products enables the user to quickly design and assemble an F/O system. A full understanding of the device characteristics and the characteristics of cables and connectors used with FOACs, gives the designer the capability to perform a flux budget analysis of his system and thus predict performance.

Specific conclusions drawn from this study are:

- **LED** — in most cases not all power as specified on typical data sheets is usable due to NA differences.
- **Fiber** — NA is not constant in short lengths of fiber when used with high NA sources.
- **Connectors** — Connector losses are dependent upon the NA conditions combined with the mechanical tolerances.
- **Detector** — Detector responsivity is specified as a function of the actual power launched into the optical input port.

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